DESIGN OF UNDERGROUND VAULTS WITH THERMAL SIMULATION OF TRANSFORMER

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ABSTRACT

This paper, that follows a companion paper [9], studies the thermal load behavior of a transformer in an underground vault so as to establish maximum economical loading in regard to the loss of life and contingencies. In that way it optimizes the annual operation cost taking into account the amortization costs of the transformer, the air forced circulation and, also, the loading of the transformer in fault conditions in the system. The study was developed in an experimental way. The losses of the transformer were simulated by a set of resistances installed inside the transformer and supplied by a 220 V external source. Switching the resistances allows simulating innumerous daily loads curves. The internal temperatures of the transformer, namely in the oil tank, and in several sites of the vault were obtained by electronic probes and were collected by a data acquisition system that supports also a remote control system that is able to survey anomalous operating conditions, switching on and off the air forced circulation and switching the resistances to match with the daily load curve desired.

INTRODUCTION

The aim of this work is the determination of the top oil temperature and in the vault so as to obtain the loss of life of the transformer in several operating conditions, that is: with or without air forced circulation, different dimensions of the vault and with a proposed daily load curve. Instead of obtaining several daily load curves by a variable load it was preferred to perform the simulation of daily load curve through a set of resistances installed into the transformer tank that is supplied by an 220 V external source. The experiment was perfomed on a 500 kVA, 13.8 kV/220 V three-phase transformer, with no load losses of 1200 W. The full load cooper losses are 5300 W. The no load losses were simulated by a 1200 W resistance, at 220 V, and the cooper losses were simulated by six 1070W resistances. By using such set of resistances, differente loading conditions may be achieved. The vault was constructed in a plant of AES-Eletropaulo. Its height, from the roof to the pavement, is 2.70 m and the initial width and length were 4.68 m and 2.30 m. In order to vary width and length dimensions, walls inside the vault were built. Table 1 shows the dimensions of the vault for each size.

Table 1 – Dimensions of the vault

Size	Length (m)	Width (m)
1	4.68	2.30
2	2.81	2.30
3	2.81	1.60

The daily load curves with maximal demand of about 76 % and 100%, with duration of peak demand of 8 hours, namely curves A and B, and 12 hours, namely curves C and D, are presented at Tables 2 and 3.

Table 2 – Daily curve - 8 h peak duration

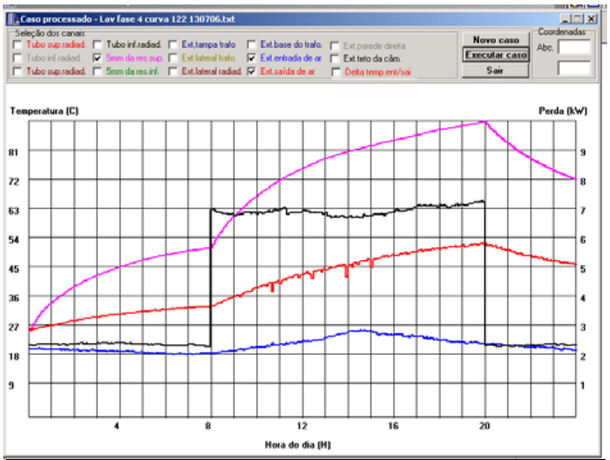
TIME (HOURS)	DEMAND (PU)	
	CURVE A	CURVE B
0 - 9	0.41	0.41
9 - 17	0.76	1.00
17 - 19	0.41	0.41
19 - 20	0.62	0.62
20 - 22	0.62	0.76
22 - 24	0.41	0.41

Table 3 – Daily curve 12 h peak duration

TIME (HOURS)	DEMAND (PU)	
	CURVE C	CURVE D
0 - 8	0.41	0.41
8 - 20	0.76	1.00
20 - 24	0.41	0.41

The data acquisition system was designed with 16 data acquisition channels, 14 for temperature and 2 for the speed and the pressure of the air in the exit duct. The system has detectors of anomalous operating conditions. For instance, if the top oil temperature exceeds 90 ^{o}C the system will be switched off. The system is powered with facilities to remote control of the resistances status, allowing the operator to switch on or off any one of the resistances at a desire time. He can also download data stored in the device´s memory. This memory has capability to store the five day measurements in 5 minute intervals. Figure 1 presents the results of the measurements of the daily load curve D.

Figure 1 – Measurement results



Convention: Black – daily load curve - Fuchsia – Top oil temperature – Blue – Input air temperature – Red – Exit air temperature

FORCED AIR CIRCULATION

Introduction

The role of forced air circulation is very important in the heat transfer from the vault to the environment. The heat transfer equation for the air flowing through the vault to the environment is:

$$Q_{vent} = V_{air}\, C_{air}\, (T_{vault} - T_{amb})$$

where:

V_{air} - air flow, kg/s;
C_{Air} - thermal capacity of air, C_{Air}, 1015 J/kg×K);
T_{Amb} - ambient temperature in air external to vault, °C;
T_{vault} - temperature in the vault, °C;

Disregarding the heat transfer through the walls and through the ceiling, the heat transferred by air to the surrounding ambient is equal to the heat produced in the transformer. Assuming a 25 °C ambient temperature, the temperature in the vault, for a operative condition of the transformer, is:

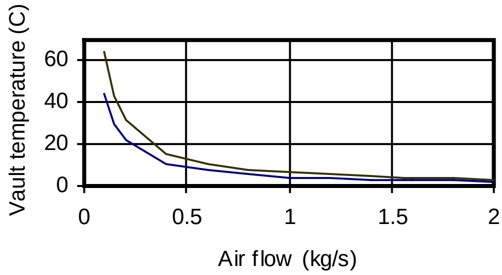
$$T_{vault} = \frac{Q_{vent}}{V_{air}\, C_{air}} + T_{amb}$$

The temperature in the vault, for the transformer at full load and at 0.6 pu is presented in Figure 2. It is observed that without air forced circulation, in steady state, the vault temperature raises about 40 °C, for full load and about 20 °C for 0.6 pu.

Annually operating cost

The costs used are:
- 500 kVA 3-phase transformer: US$16,000;
- Vault of size A, B and C, respectively, US$20,000, US$18,800.00 and US$15,000;

Figure 2 - Vault temperature



- Motor-fan and ducts for forced air circulation: US$1,400.00;
- Demand cost, C_{Dem} = 183.00 US$/kW/year;
- Energy cost, C_{ε} = 0.12 US$/kWh.

The annually operating cost includes:

– Vault amortization cost, that is:

$$C_{Amor,Vault} = \frac{j}{1-(1+j)^{-L_{Vault}}} C_{Vault}$$

Assuming the interest rate j 12 % per year and the live of the vault, L_{Vault} , 40 years, results:

$$C_{Amor,Vault} = \frac{0.12}{1-1.12^{-40}} C_{Vault} = 0.1213 C_{Vault}$$

and the annual cost of the vaults of sizes A, B and C are, respectively, US$2,426, US$2,280 and US$1,820

– Transformer amortization cost that takes into account the transformer life, L_{Trans}, which depends on the daily load curve;

– Cost of losses of the transformer that includes no load losses, iron losses, which are constant during the year and cooper losses that depend on the daily load curve. Assuming that P_{nl} is the no load loss, the corresponding cost is given by:

$$C_{nl} = P_{nl}\,(C_{Dem} + 8760\, C_{\varepsilon})$$

The cost of no load losses is the same for all the daily curves, equals to 1,481 US$/year. The annual cost of cooper losses depends on the daily load curve, and can be given by:

$$C_{Cooper\,loss} = s_{max}^2 P_{coop,fl} C_{Dem} + 365\, P_{coop,fl} C_{\varepsilon} \int_0^{24} s_i^2\, dt$$

$$C_{Cooper\,loss} = A_{Dem} C_{Dem} + B_{Energy}\, C_{\varepsilon}$$

where:

$P_{coop,fl}$ – full load cooper losses;
s_{max} – maximum demand;
s_i – demand at time "i".

The costs of cooper losses are presented in Table 3.

Table 3 – Cost of losses

Daily load curve	Cost of cooper losses (US$/year)	Cost of losses (US$/year)
A	2410	3891
B	3693	5174
C	3058	4539
D	3822	5303

- Motor fan amortization, if it is used in the alternative assuming life of 10 years, is given by:

$$C_{f.air} = 1400\,\frac{0.12}{1-1.12^{-10}} = 247.80\,US\$/year$$

- Cost of the energy absorbed by the motor of the fan. This cost depends on the period the motor is running. The power absorbed by the motor is 2.5 kW.

Results of field tests

Table 4 shows the estimated life of the transformer, which results from test fields. The life was estimated assuming that at full load the elevation of the temperature of the hot spot is 25 °C. The top oil temperature was measured experimentally, so the loss of life was calculated by [7]:

$$LF\% = 100\sum_{i=0,\tau} 10^{-\left(-14.133+\frac{6972.15}{T_{hs}(i)}\right)}$$

Table 4 – Life estimated of transformer (year)

Daily curve	Air circulation	Size 1	Size 2	Size 3
A	Natural	121.6	101.73	92.7
B	Natural	7.3	5.61	5.0
	Forced daily	54.5	53.60	53.3
	Peak load forced	32.6	25.01	15.5
C	Natural	83.4	67.69	61.7
D	Natural	4.1	3.15	2.8
	Forced daily	31.2	30.77	30.6
	Peak load forced	25.8	18.17	12.4

Evidently, from the results, when loading the transformer up to 70 %, the use of air forced circulation is not needed. And, also, the vault of Size 3, the smallest, may be built without any trouble. On the other hand, when the loading is about 100 %, the life gets too short and air forced circulation is recommended. The results when comparing the use of forced air circulation during all day long and only during the daily peak load are shown in Tables 5 and 6. The maximum transformer's life was assumed to be 45 years. The transformer's losses were disregarded because they are the same for the three sizes. The demand of the motor-fan set to force air circulation is 2.5 kW.

From the results in Tables 5 and 6, it is quite evident that the optimal operating condition is that in which the forced air circulation is switched on only during the peak demand of the transformer. Comparing, also, the differences of the cost between sizes, it is evident that the small vault is the most inexpensive.

Using the computational system developed in [9] it is possible to establish the variation of the expected life as a function of the transformer loading, as shown in Figures 2 and 3, for daily load curves A and C, respectively.

Table 5 – Operational transformer cost (US$/year) – curve A

Air circulation	Annual cost	Size1	Size 2	Size 3
Natural	Vault	2426	2280	1820
	Transformer	3400	4081	4452
	Total	**5826**	**6361**	**6272**
Forced air daily	Vault	2426	2280	1820
	Transformer	1932	1932	1932
	Ventilation	248	248	248
	Loss ventilation	3086	3086	3086
	Total	**7692**	**7546**	**7086**
Forced air during peak load	Vault	2426	2280	1820
	Transformer	1987	2040	2321
	Ventilation	248	248	248
	Loss ventilation	1029	1029	1029
	Total	**5690**	**5597**	**5418**

Table 6 – Operational transformer cost (US$/year) – curve B

Air circulation	Annual cost	Size1	Size 2	Phase 3
Natural	Vault	2426	2280	1820
	Transformer	5176	6395	7061
	Total	**7602**	**8675**	**8881**
Forced air daily	Vault	2426	2280	1820
	Transformer	1978	1981	1982
	Ventilation	248	248	248
	Loss ventilation	3086	3086	3086
	Total	**7738**	**7595**	**7136**
Forced air during peak load	Vault	2426	2280	1820
	Trans	2029	2201	2548
	Ventilation	248	248	248
	Loss ventilation	1543	1543	1543
	Total	**6246**	**6272**	**6159**

OPERATION WITH NETWORK IN FAULT CONDITIONS

When looking for the optimal loading of a transformer installed in an underground vault, it is important to have in mind that it operates in the planned maximum demand during the major part of the year. Just for some days, e.g. from one to ten, it operates overloaded due to faults. When taking this contingency condition into account, the estimated life may be calculated by:

$$\text{Life} = \frac{100}{(365 - n_{fault}) \times DLL_{Normal} + n_{fault} \times DLL_{Fault}}$$

where:

- DLL_{Normal} - daily loss of life for normal operation

– DLL_{Fault} - daily loss of life for operation with network fault condition;
– N_{Fault} - number of days it operates with network fault condition.

It was assumed that for both A and C daily load curves, the transformer is operating with 76 % peak demand and, in fault conditions , at the 103 % maximum demand. Figures 4 and 5 show the results for curves A and C, respectively.

CONCLUSIONS

From the study carried out, it is possible to conclude that:

– It is convenient to use forced ventilation for long peak duration and high demand load curves, regardless the size of the vault. This is the case for daily load curve D shown in the paper.
– Significant energy savings in forced ventilation supply are noted when this is on only during peak hours, as shown in Table 5 (lower operational costs). Air forced circulation is switched on when the vault temperature reaches 50 °C and switched out when it falls below 45 °C.
– Natural ventilation is sufficient to ensure an adequate estimated life in transformers, when the demand is at moderate levels, as it is the case of daily load curves A and C.
– The estimated life is greater than 30 years for transformers operating with no air forced circulation, provided that the daily peak load is less than 80% at normal conditions and less than 105% during fault conditions (less than 15 days per year).

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Figure 2 - Transformer life - Curve A

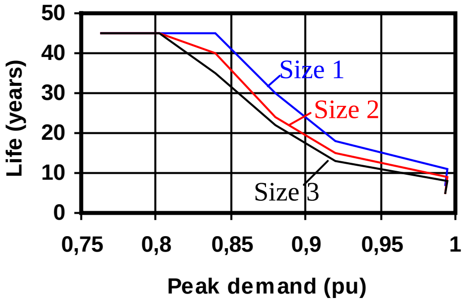

Figure 3 Transformer life - Curve C

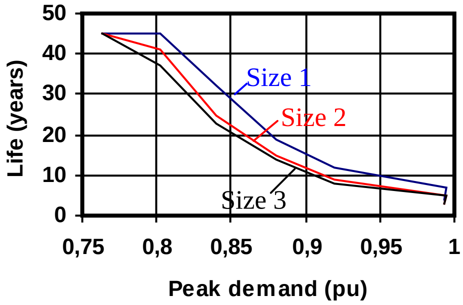

Figure 4 - Transformer with faults

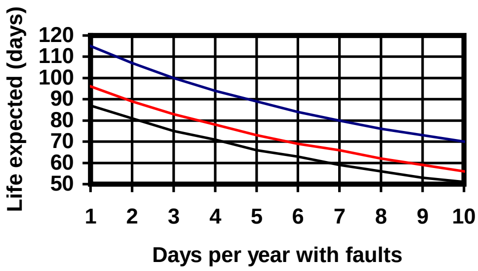

Figure 5- Transformer with faults